10/526403

DT06 F[illegible] PCT/PTO 02 MAR 2005

DOCKET NO.: 266456US6PCT

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IN RE APPLICATION OF: Andrew J. WHITEHEAD, et al.
SERIAL NO.: NEW U.S. PCT APPLICATION
FILED: HEREWITH
INTERNATIONAL APPLICATION NO.: PCT/IB03/03762
INTERNATIONAL FILING DATE: September 4, 2003
FOR: DIAMOND RADIATION DETECTOR

**REQUEST FOR PRIORITY UNDER 35 U.S.C. 119
AND THE INTERNATIONAL CONVENTION**

Commissioner for Patents
Alexandria, Virginia 22313

Sir:

In the matter of the above-identified application for patent, notice is hereby given that the applicant claims as priority:

COUNTRY	APPLICATION NO	DAY/MONTH/YEAR
Great Britain	0220767.8	06 September 2002

Certified copies of the corresponding Convention application(s) were submitted to the International Bureau in PCT Application No. PCT/IB03/03762.

Respectfully submitted,
OBLON, SPIVAK, McCLELLAND,
MAIER & NEUSTADT, P.C.

Surinder Sachar

Gregory J. Maier
Attorney of Record
Registration No. 25,599
Surinder Sachar
Registration No. 34,423

Customer Number
22850

(703) 413-3000
Fax No. (703) 413-2220
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Full name, address and postcode of the or of each applicant *(underline all surnames)*	**Diamanx Products Limited** **Isle of Man Freeport** **Ballasalla** **Isle of Man, U.K.** **IM99 6AQ**	
Patents ADP number *(if you know it)*	07153752002	
If the applicant is a corporate body, give the country/state of its incorporation	**Isle of Man, U.K.**	
Title of the invention	**Diamond Radiation Detector**	
5. Name of your agent *(if you have one)*	**Carpmaels & Ransford**	
"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	**43 Bloomsbury Square** **London** **WC1A 2RA**	
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Signature Carpmaels & Ransford
Carpmaels & Ransford

Date **6th September 2002**

12. Name and daytime telephone number of person to contact in the United Kingdom **Mr. A.J. Jones** **020-7242 8692**

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DIAMOND RADIATION DETECTOR

BACKGROUND OF THE INVENTION

This invention relates to a diamond radiation detector.

Diamond is well known as a potential radiation detector. Its advantages include high radiation hardness, high thermal conductivity, rigidity, and simplicity of the detector design. However, its application has not been as widespread as anticipated, because of a range of practical problems.

Polycrystalline diamond radiation detectors are currently being assessed for a range of applications including particle detectors for the large hadron collider (LHC). In this application, radiation hardness is paramount, but another requirement is good separation of signal from background noise. Based on the particular signal characteristics exhibited by polycrystalline diamond, application of this material requires a charge collection distance (CCD) of at least 250 μm. This value is now just achievable in polycrystalline diamond, but the required grade is substantially more difficult than other polycrystalline grades to manufacture. The 250 μm collection distance is achieved by using very high quality polycrystalline diamond layers about 500 μm thick, and an applied field of 1 V/μm, equivalent to a voltage of about 500 V. It is found that the CCD in polycrystalline CVD (chemical vapour deposition) diamond rises rapidly with applied field, achieving 90% of saturation at about 0.8 V/μm and approaching saturation by about 1 V/μm (i.e. the CCD no longer increases when the field is increased) [see, for example, a) Zhao. S. (1994), PhD Thesis 'Characterization of the Electrical Properties of Polycrystalline Diamond Films', The Ohio State University, b) W Adam et al (The RD42 Collaboration), Nucl. Instr. Methods in Phys. Res. A434 (1999) pp131-145].

Measurements of the CCD of natural single crystal diamond as a function of applied field suggests that it has not saturated even at 2 V/μm [see, for example, Zhao. S. (1994), PhD Thesis] offering one route to higher CCD values, although exacerbating the problems of using higher voltages. However, the maximum CCD measured with such crystals is reported to be about 40 μm at 2 V/μm applied electric field.

WO 01/96633 discloses a high purity single crystal diamond produced by chemical vapour deposition. The diamond has a high resistivity, a high breakdown voltage in the off state, high electron mobility and hole mobility and a high charge collection distance measured at 1 V/μm. The diamond is described as being useful in electronic applications, particularly as a detector element or switching element.

SUMMARY OF THE INVENTION

It has now been found that the charge collection distance of single crystal CVD diamond, particularly that described in WO 01/96633, rises very rapidly with the applied field, and particularly in samples of the order of 1000 μm thick or less, and achieves near saturation (maximum obtainable charge collection distance) at much lower applied fields than 1.0 V/μm. In particular, 90% of the maximum obtainable charge collection distance (i.e. 90% saturation) can be achieved at applied fields as low as 0.25 V/μm.

In use, the benefit is that at 0.25 V/μm the diamond of the invention can still exhibit CCD values as high as 510 μm in samples 550 μm thick and operate in a region where the device is not sensitive to small variations in the bias voltage. In contrast, conventional polycrystalline diamond operated at

0.25 V/μm would show typically only 70% of the (substantially lower) saturation CCD and be operating in a region where small changes in bias voltage caused large variation in signal, thus degrading device stability and performance.

The invention further provides a detector comprising a single crystal CVD diamond which achieves 90% of saturation with an applied field of less than 0.7 V/μm, and preferably less than 0.5 V/μm, and more preferably less than 0.3 V/μm. The diamond has applied to it a field of less than 0.7 V/μm, and preferably less than 0.5 V/μm, and more preferably less than 0.3 V/μm. With a detector of thickness of 500 μm, operated at 0.25 V/μm, the applied voltage can then be as low as 125 V.

The invention further provides a thin detector element capable of being operated at low bias voltages. In particular, the invention provides a single crystal CVD diamond less than 450 μm thick, more preferably less than 350 μm thick and even more preferably less than 250 μm thick, which achieves 90% of saturation with an applied field of less than 0.7 V/μm, and preferably less than 0.5 V/μm, and more preferably less than 0.3 V/μm. With a detector of thickness of 250 μm, operated at 0.25 V/μm, the applied voltage can then be as low as 63 V whilst still achieving charge collection distances of the order of 250 μm, as is required for many applications.

Thus the diamond detector of the invention generally exhibits high charge collection efficiency even at these low applied fields, generally achieving values greater than 50%, and typically greater than 75%, and more typically greater than 85%, and even more typically greater than 90%.

The single crystal CVD diamond for use in the invention is preferably high purity single crystal CVD diamond, preferably that described in WO 01/96633, particularly a thin layer of such diamond.

The detector of the invention has particular application in stand-alone, remote or hand-held devices, where provision of high bias voltages may be difficult or costly.

The detector also has particular application where the radiation being detected can be deleteriously scattered, absorbed or otherwise affected by the detector. As the interaction between the radiation and the detector is generally a function of the thickness of the detector element, a thinner detector exhibiting a similar high charge collection distance is beneficial.

DESCRIPTION OF EMBODIMENTS

The invention provides an improved radiation detector that provides useful functionality at lower operating voltages and uses thinner diamond layers compared with existing diamond detectors. The detector can be used for the direct detection of radiation such as beta particles (high energy electrons), alpha particles, protons, other high-energy nuclear particles (pions etc) and high-energy electromagnetic radiation (X-rays, gamma rays etc), and for the indirect detection of neutrons. It is particularly suitable for use in stand-alone hand-held and remote sensor systems.

As mentioned above, the detector of the invention may be used at much lower bias voltages than polycrystalline CVD diamond or natural diamond, for example. The use of lower bias voltages allows the detector to be used in less expensive, simpler systems, and in remote or hand-held devices. For example, a 250 µm thick high purity single crystal CVD diamond detector requires an applied bias of only 63 V to obtain adequate performance. A conventional detector based on a photo-multiplier tube (PMT) would require a supply voltage of, for example, 1 kV to operate. A particular example of remote detection where the reduced voltage would be a considerable benefit is

the 'logging' of wells drilled for oil exploration. Here the detector is in a very hostile environment (both thermally and mechanically) and provision of a high voltage power supply is very difficult. The robust, low voltage, solid-state detector of the invention would be much easier to operate than the conventional high voltage PMT-based detectors.

A further advantage of the detector of the invention is that since the detecting layer is thinner than known polycrystalline diamond and natural diamond detectors, the particles to be detected interact less with, and are thus affected less by, the detector. This is a very important consideration in applications such as high-energy physics (e.g. LHC), where high performance detectors are required, but in addition the radiation being measured may be required to pass through many detector elements essentially unimpeded.

The high purity single crystal CVD diamond layer which is used in the radiation detector of the invention is typically a polished plate between 10 μm and 1000 μm thick, and more typically between 100 μm and 400 μm thick. Ohmic contacts may be formed either on both surfaces, as in a 'sandwich' structure, or on one surface only, as in an interdigitated array. Such ohmic contacts may be formed using methods known in the art.

A dc bias is applied between the two electrodes such that the field is the saturation field of the detector using a high-resistance supply (e.g. Keithley 237 Source-Measure Unit). One electrode is also connected to a charge measuring system, for example a charge sensitive amplifier, so that the signal can be read out.

The detector is placed in a beam of high-energy nuclear particles such as beta particles or pions and the output signal is monitored. When a particle transits the detector, a signal will be detected.

The invention will be illustrated by the following examples.

Example 1

Beta particle or high-energy nuclear particle (e.g. pion) detector.

A conventional diamond particle detector is made from the best available polycrystalline CVD diamond (see for example Adam, W. *et al* (2000), 'Micro-strip sensors based on CVD diamond', Nuclear Instruments and Methods in Physics Research A, 453, 141-148). The detector is 500 μm thick. The detector is irradiated with, for example, beta particles from a strontium-90 source or pions or protons from a particle accelerator beam line. The detector yields, at a saturation bias of 500 V (equivalent to an electric field of 1 V/μm), about 7000 electrons per particle passing through the detector. This is equivalent to a charge collection efficiency (CCE) of ~ 39%. The charge of 7000 electrons is sufficient for a particle detector to operate with current back-end signal processing electronics.

A layer of high purity single crystal CVD diamond described in WO 01/96633, 500 μm thick, has been found to have a CCE of greater than 95% at 1 V/μm. Therefore to collect the required 7000 electrons generated by a minimum ionising particle (which generates 36 electron/hole pairs per micron of detector material traversed), the detector only needs to be 210 μm thick. Further, it has been found that such detectors using such a diamond layer of the invention has essentially saturated at a field of 0.3 V/μm, and achieved 90% saturation at a field of < 0.25 V/μm. A plot of the saturation curve (measured CCD versus applied voltage) is shown for a 550 μm thick sample in Figure 1. These measurements indicate that it would be possible to reduce the thickness of the detector to 235 μm and the bias voltage to 60 V and still collect 7000 electrons.

Example 2

Alpha particle detector.

A high purity single crystal CVD diamond plate as described in WO 01/96633, about 200 μm thick, was prepared with Ti-Au electrodes on both sides ('sandwich' configuration). It was connected to a 100 V bias and one electrode is connected to a multichannel analyser. The detector was irradiated in vacuum with 5,5 MeV alpha particles from an Americium-241 radioactive source.

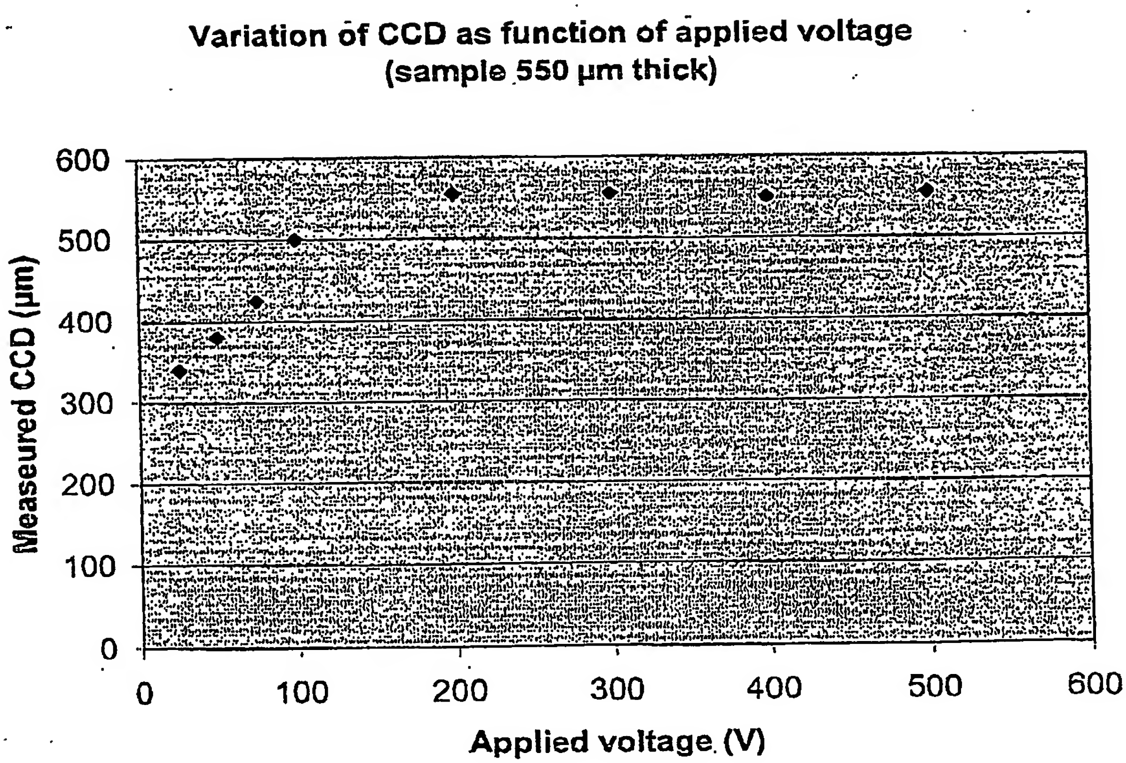
The output from the multichannel analyser was a single, narrow peak (full width at half maximum of ~ 0,18 MeV) with a signal to noise ratio of approximately 50 (Figure 2). Alpha particle detectors reported made from polycrystalline CVD diamond and reported in the literature (e.g. Foulon, F. *et al* (1998) 'Neutron detectors made from chemically vapour deposited semiconductors', Mat. Res. Soc. Symp. Proc., 487, 591-596) have a broad ill-defined peak that is not useful as a detector. The diamond detector of the invention can thus be used as an alpha particle detector for, for example, well logging.

Example 3

Neutron detector.

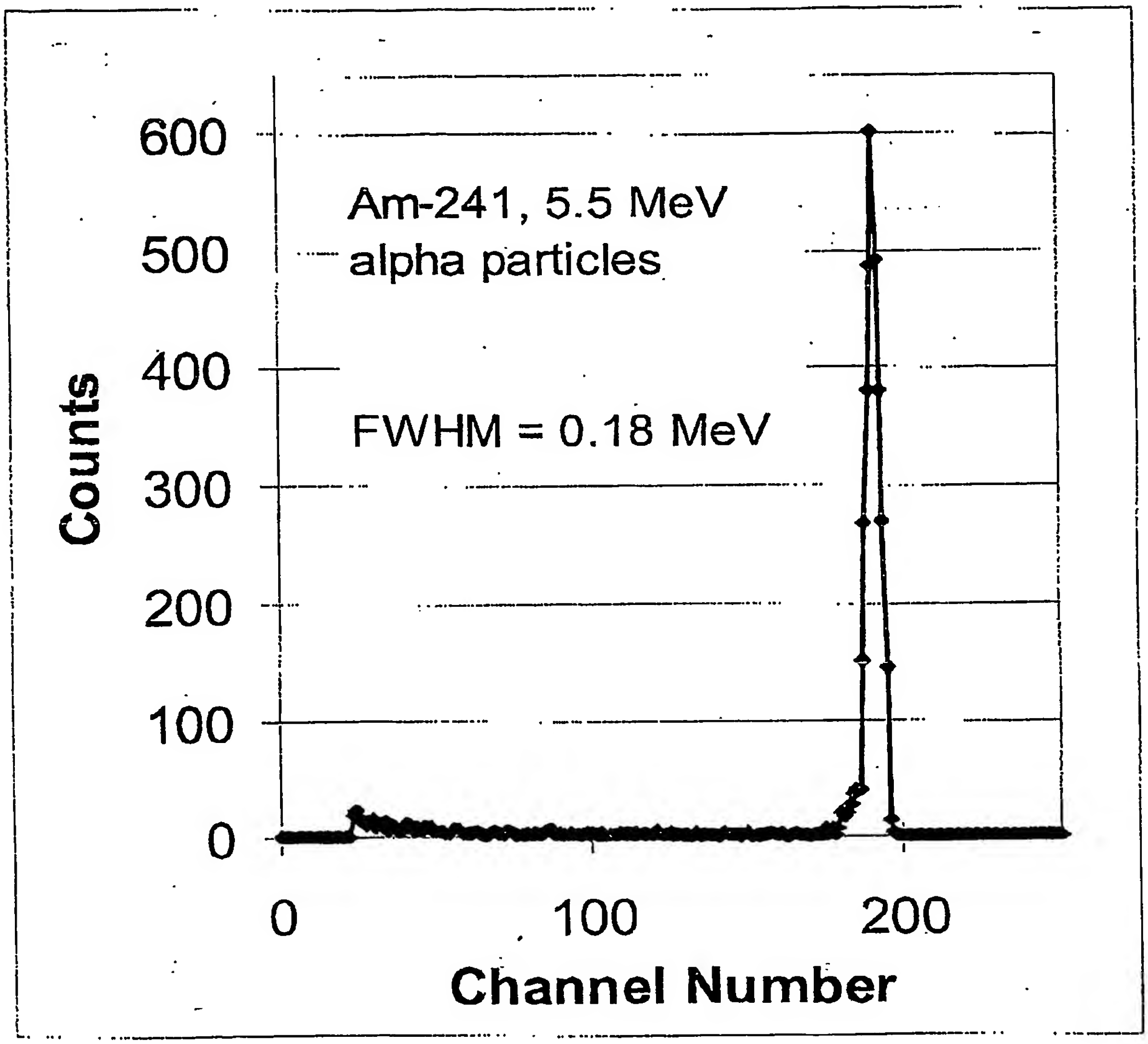
A neutron detector is prepared in a similar manner to the alpha detector described in Example 2 except that an additional 'converter layer' of material with a high neutron capture cross section, such as Boron-10, is placed on or adjacent to one electrode. The thickness of the converter layer is typically 0,1 - 10 μm thick. With a boron-10 converter layer, each captured neutron yields an alpha particle. Some of the alpha particles enter the diamond and are detected.

Figure 1



Variation of CCD as function of applied voltage
(sample 550 µm thick)
600
500
400
300
200
100
0
Measeured CCD (µm)
0
100
200
300
400
500
600
Applied voltage (V)

Figure 2



Am-241, 5.5 MeV
alpha particles
FWHM = 0.18 MeV
Counts
600
500
400
300
200
100
0
0
100
200
Channel Number

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